3DSCINT – Commodification of Scintillator Detectors using 3D Printing Techniques

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ABSTRACT

High quality scintillator detectors for the tracking of elementary particles require accurate positioning of large numbers of scintillating elements with complex arrangements. The 3DSCINT project aims to commodify scintillator technologies through 3D-printing of holding structures that are integrated with the scintillating fibres and readout electronics. 3D-printing makes it possible to use complex, conformal, modular, scalable and low-cost detector structures. It represents a step change to current laborious manufacturing methods, lowering cost and improving the viability of large-scale applications. The project was successful within its aims, resulting in the production of scintillator holding structures and matching electronics.

Keywords: 3D printing, Scintillator, Muon tomography

1. INTRODUCTION

Scintillator technologies are an integral part of particle detectors in fundamental particle, nuclear, medical and applied physics applications worldwide. These research systems typically are bespoke, one-off detectors designed for high-performance and permanent installation within controlled and routinely monitored environments.

The 3DSCINT project aims to revolutionise and commodify the use and application of scintillator technology through the integration of state-of-art 3D printing technology with scintillator materials and electronics.

The project focuses on the use of rapid additive manufacturing technologies for the manufacturing of scintillating fibre and silicon photomultiplier holding structures with the ultimate goal to manufacture modular, rapidly customisable and scalable, low cost structures.

The first application for this innovative detector manufacturing technique lies within the non-destructive testing field of cosmic-ray muography: a passive imaging method that uses natural background radiation to inspect the contents of complex, shielded structures (such as bridges or nuclear waste containers). A recent, and quite spectacular, success that illustrates the capabilities of muography was the discovery of a large cavity inside the Pyramid of Khufu in 2017 [1]. Large scale application of the technology is currently limited by cost and complexity of manufacture of the detectors.

The project was developed in partnership by Swansea University (3D printing technology) and Lynkeos Technology Ltd. (muon tomography).

The project was successful within its aims, resulting in the production of scintillator holding structures and matching electronics, capable of 2D mapping of cosmic-ray muon tracks. Fused deposition modelling (FDM) 3D printing was selected as the manufacturing process for its ability to print internal channels, whilst avoiding the use of support materials, preventing the risk of contaminating scintillating fibres with residual support material. As part of the project, two structures were fabricated: a modular flat panel with integrated electronics, suitable for general structure testing; and a small cylindrical structure, suitable for future deployment in bore-holes. Importantly, the success of the project is paving the way for future research and development and commercial exploitation.

2. STATE OF THE ART

3D printing is a rapidly evolving area [2]. One field explored by the scientific community is the direct printing of scintillating materials [3-4]. While this is in principle highly promising, it is still in the early stage of development and the performance of resulting detectors is significantly lower than traditionally manufactured scintillator materials. The 3DSCINT project takes a different approach by integrating 3D printed polymer scaffolds with existing scintillator materials (e.g. fibres). This is a new approach previously not yet explored by the scientific community in nuclear and particle physics.

Lynkeos is at the forefront of the field of cosmic-ray muon imaging, having commercialised its Muon Imaging System (MIS), as the world's first CE Certified muography system and the first system of its kind worldwide to be deployed on a nuclear licensed site (Sellafield, UK)[5]. The detectors used in the Lynkeos MIS are currently handcrafted, requiring highly specialised people and extensive construction time. Integration of modular, rapidly customisable and scalable, low cost structures via 3D-printing will be a game changer opening a new dimension in terms of scale of manufacture.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

By combining 3D printing for the manufacture of holding structures with existing scintillator materials, 3DSCINT aims to revolutionise the manufacturing of scintillator detectors, making them scalable and affordable, opening commercial opportunities for wider scale adoption and the development of mobile units.

High quality detectors, capable of 2D mapping and tracking of elementary particles requires accurate positioning of large numbers, typically thousands, of scintillating fibres with complex arrangements. 3D printing offers the opportunity to rapidly and precisely produce matching supporting structures. This is due to its manufacturing design flexibility (such as convoluted internal channels) and high precision and accuracy. 3D-printing acts as a game changer: it provides a step change in manufacturing speed and offers lower costs compared to current solutions, whilst also enhancing the potential performance of scintillator detectors by providing a repeatable, consistent arrangement.

4. PROJECT RESULTS

4.1. Working Principle

Figure 2 shows an "exploded" view of the CAD design of the components for the presented muon detector. Muons that cross the scintillating fibres produce a light signal in the scintillating fibres that is registered by the Silicon Photomultipler (SiPM) sensor array at the end of fibre. The fibres are encased inside the scaffolding structure, which acts as mechanical protection, light proof protection and as a guide to the fibres, facilitating easy manufacturing and assembly.

4.2. 3D-Printing

The 3D-printing for this project was performed at Swansea University, using a fused deposition modelling process to produce scintillating fibre holding structures consisting of a solid structure with hollow channels. Multiple 3D printers and printable polymers were tested. The presented results were printed on purposely adapted Prusa i3 MK3S adopting polylactic acid (PLA) as the material (Figures 1-2-3).

In the presented design of the holding structure (122mm x 122mm x 14mm) (see Figure 1) the channels run horizontally with a pitch of 3.5 mm (spacing imposed by SiPM sensor chip) over 4 stacked layers. The channels have a narrow width sufficient to thread the fibres (nominally 2 mm diameter) through without causing damage to them.

The fibre matrix was designed to match the frequency of fibres allowed by the spacing of the SiPM sensors (3.4mm x 3.4 mm each in an array layout with 0.1 mm gap) This was done to maximise the frequency of hollow channels: arranging the channels over multiple phased layers and in perpendicular directions, to optimise the area covered by the inserted scintillating fibres and to maximise resolution and sensitivity for muon detection. Print and design parameters were optimised to be able to print the structure without the need for support materials whilst also creating defect-free openings.

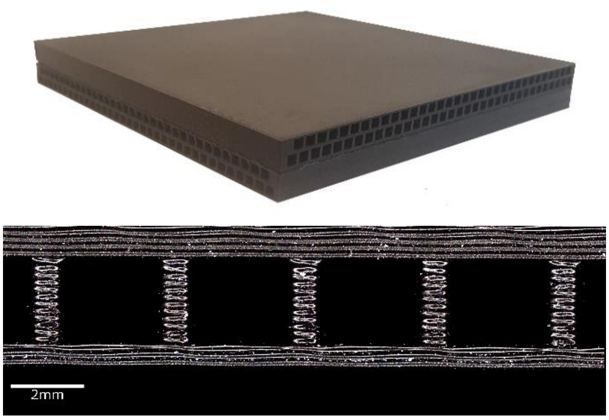

Fig. 1. Top: A photograph showing the 3D printed scintillating fibre holding structure, and Bottom: A microscope image showing the channels/openings through the 3D printed structure (scale bar for reference is 2mm).

An enclosure was also developed to house the flat-panel scintillating fibre holding structure as well as the necessary detection electronics, including the matching SiPM. This was designed/printed to precise measurements, ensuring accurate alignment of each of the silicon multipliers with the fibres located in the channels whilst also limiting the amount of noise caused by ambient light. Fig 2 shows a 3D CAD rendering of the complete 3D printed scintillator fibre holding structure with enclosure, circuit boards and mounting accessories.

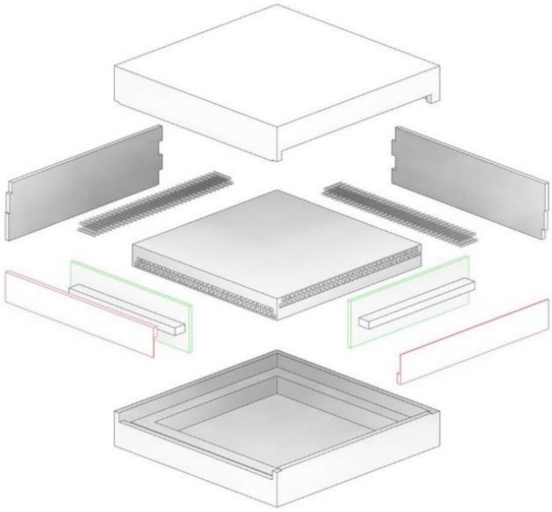

Fig. 2. A CAD rendering showing the final 3D printed detector holding structure, enclosed to reduce light interference and improve circuit board support. The SiPM sensor arrays are in green outline colour. Scintillating fibres are inserted in scintillator holding structure in the centre of the image.

Fig 3 shows the final assembled 3D printed parts with openings for external connections of the the detection electronics

Fig. 3. A photograph showing the complete assembly of 3D printed parts, with openings for external connections.

4.3. Electronics Development and Validation

The prototype detector is based on Saint Gobain BCF12MC fibres and Hamamatsu S14160-3050HS SiPMs. The SiPMs are arranged in a double-row, alternating matrix that corresponds to the fibre channels in Fig 1. Fig 4 shows a passive interface board that was developed to interface 32 SiPMs with a Caen A1702 frontend board. This system allowed for the testing of a 3D printed support structure, as shown in Fig 1, which was partially filled with 24 scintillating fibres, split across two layers. These fibres were then mechanically coupled to matching SiPMs which were then biased and read out with a single Caen A1702 frontend board.

Fig. 4. A photograph showing a prototype printed circuit board with 32 Hamamatsu SiPMs.

The readout was tested with a simple linear scintillating fibre array with 32 fibres that directly matched the SiPM array and with part of a square module as in Fig 1. The number of readout channels was limited to a single PCB.

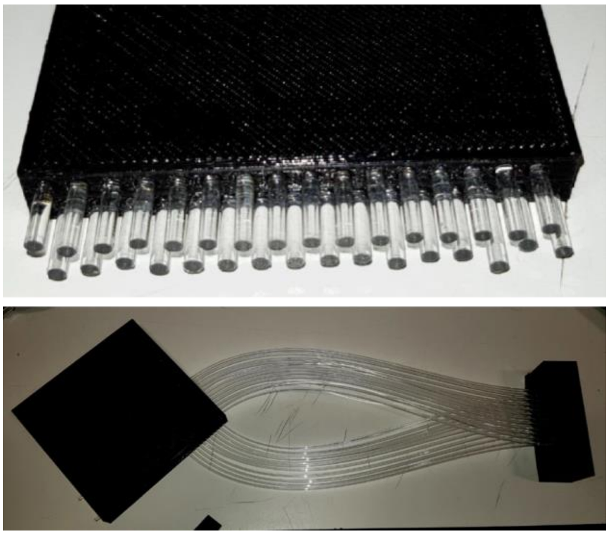

Fig. 5. Top: Linear array of 32 fibres in two layers, Bottom: readout of a 3D-printed two-dimensional array, partially filled with scintillating fibres. The operation of the square array was verified with cosmic-ray muons and with a ^{90}Sr beta source. The histogram in Fig 6 shows cosmic-ray data collected over several hours. It clearly shows the points of intersection of the scintillating fibre matrix, due to coincident events occurring in both layers of fibres.

The structure which can be seen in the data in Fig 6 is due to an increase of coincident events caused by crosstalk between channels at the PCB. This will be remedied by separating the channels between two separate PCBs in future experiments. Fig 7 demonstrates the good position resolution and low cross talk that was achieved with the beta source.

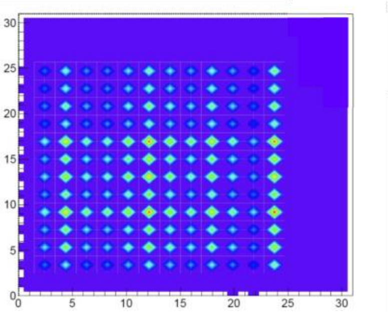

Fig. 6. A 2D histogram of hits from cosmic ray muons on the set up shown in Fig 5. The points at which the fibres cross can easily be seen, showing the expected regular square grid and 144 crossover points.

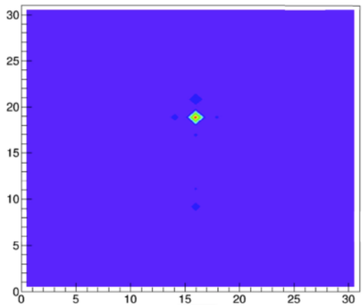

Fig. 7. Response of the 2D detector array to a ^{90}Sr beta source.

4.4. Printing of Conformal Scintillator-fibre holding structures

In addition to the flat-panel scintillating fibre holding structure shown in Fig 1-3, a cylindrical design was also manufactured. This style of fibre holding structure differs as it contains two sets of spiral channels running in opposite directions, one clockwise and one anticlockwise. Fig 8 shows a photograph of the 3D printed cylindrical fibre-holding structure. Such a structure would be the ideal basis for a borehole detector.

Fig. 8. A photograph showing the 3D printed cylindrical scintillating fibre holding structure with 4 exposed fibres.

5. FUTURE PROJECT VISION

The overall long-term vision of the 3DSCINT project is the commodification of particle detectors, specifically scintillator detectors. Muon tomography is the first application that we selected, because it would especially benefit from modular and mobile scintillating fibre detectors. In fact, the idea for 3DSCINT had grown out of the necessity to develop a mobile muon imaging system and realising the wider potential of the technology.

We now see that the next steps to realise this technology will require more focus. Following market research carried out on behalf of Lynkeos Technology we have recognised that the most promising direction for our technology is civil engineering, in particular the monitoring of bridges. After the collapse of the Morandi bridge in Genoa in 2018 this has been an area that has attracted a lot of attention. The market research has confirmed that there is a market for a mobile muon imaging system for civil engineering applications. We are therefore planning to concentrate our future efforts in this direction.

5.1. Technology Scaling

The 3DSCINT technology is currently, after ATTRACT Phase 1, at TRL3/4, i.e. a proof-of-principle has been accomplished and a small-scale single detector has been shown to work in a laboratory environment. The next logical steps should be a small-scale multi-detector system that can function as a small muon tomography system that can be taken to the site of an application (TRL5). This would be followed by a full-scale prototype at TRL7. Key tasks along the way to a full-scale prototype include a low-power readout system for SiPMs, the alignment software and the optimisation of the 3DSCINT 3D printed scintillating fibre matrix for the construction of larger area detectors. 0

5.2. Project Synergies and Outreach

To reinforce our consortium, we have started additional collaborations with the German Bundesanstalt für Materialforschung und –prüfung (BAM) in Berlin and the European Forum of Highway Research Laboratories (FEHRL) in Brussels. BAM is a leading laboratory in non-destructive testing for civil engineering applications. We have worked with them over the course of the last year and have just submitted the worldwide first comparative study of muon tomography, ground-penetrating radar and ultrasound for publication [6].. FEHRL is the organisation of all national highway research laboratories in Europe. They are especially experienced in all aspects of public dissemination and outreach and would take over these functions in a potential ATTRACT Phase 2 project.

Through our new contacts at BAM and FEHRL we have already been able to gain access to the German duraBAST facility in principle, for future test measurements. The duraBAST facility includes a highway bridge used solely for research purposes.

5.3. Technology application and demonstration cases

The main demonstration of our technology in ATTRACT Phase 2 would be measurements carried out on a highway bridge at the duraBAST facility operated by the German Bundesamt für Strassenbau (BAST). Another application is the imaging of the contents of nuclear waste containers in situ and the verification of the contents of dry storage casks for spent nuclear fuel.

The common thread and main outcome of these applications is safety – increased safety of bridges and hence transport and increased safety of nuclear waste. This ties in with the societal challenges '*Secure, clean and efficient energy'* and *'Smart, green and integrated transport'.*

The availability of modular, simple scintillating fibre detectors in variable geometries would also benefit European Research Infrastructures in nuclear and particle physics and those that use nuclear and particle physics methods for their research.

Lynkeos Technology is currently carrying out a feasibility study for the European Spallation Source (ESS) in Lund, Sweden.

5.4. Technology commercialization

Through discussions with potential customers and investors we have learned that we first have to be able to demonstrate the technology in the form of a full-scale prototype in a relevant environment (i.e. about TRL7) before we can expect substantial investment or orders.

We have several potential customers that have expressed that they would use the technology if a mobile muon imaging system would be available.

5.5. Envisioned risks

The most obvious technical risk is the precision of the 3D printing of larger area structures or modules that are used to form larger structures. Most other risks are relatively generic for any such project – timelines that are maybe not met, key personnel that could leave or delays in obtaining CE certification for the prototype.

The best mitigation strategy for technical risks is an experienced team, which we have. The mitigation strategies for the more generic risks lie in competent project management, which we also can provide.

5.6. Liaison with Student Teams and Socio-Economic Study

In a potential ATTRACT Phase 2 project we would likely rely on our new collaborators at FEHRL to produce outreach materials at MSc. Level. They have an extensive track record in this area and they are also experienced in socio-economic studies and would provide our interface to those as well.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] ScanPyramids, http://www.scanpyramids.org/, accessed 20 August 2020
[2] Ngo T.D. et al., 2018, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, Composites Part B: Engineering, 143:pp 172-196
[3] Kim D.-g. et al., 2020, Performance of 3D printed plastic scintillators for gamma-ray detection, Nuclear Engineering and Technology, (in press) https://doi.org/10.1016/j.net.2020.05.030
[4] Dosovitskiy G.a. et Al., 2017, First 3D-printed complex inorganic polycrystalline scintillator, CrystEngComm,19: pp 4260-4264
[5] Mahon, D. et al., 2018, First-of-a-kind muography for nuclear waste characterization, Philosophical Transactions of the Royal Society A 377 (2137), 20180048
[6] Niederleithinger, E. et al., 2020, https://arxiv.org/ftp/arxiv/papers/2008/2008.07251.pdf